SensorShoe: Mobile Gait Analysis for Parkinson's Disease Patients

- User Interface Design Report -

P.J.M. Havinga

R.G. Kauw-A-Tjoe

M. Marin-Perianu

J.P. Thalen

Faculty of Engineering Technology

Faculty of Electrical Engineering, Mathematics and Computer Science

University of Twente

Table of Contents

1.Introduction

1.1.Motivation

The main source of inspiration for this project is a similar project called GaitShoe[1]. In this project, a shoe equipped with sensors can analyse the walking behaviour (*gait*) of a user, and provide the user with helpful feedback. The focus of the project was with the development of the sensors and electronics, and the analysis of sensor data. The sensors send their data through a wireless connection with a computer system, which would translate the data to gait cues.

Fig. 1: The GaitShoe sensor-set, attached to a normal shoe

The report of the project recommends several useful applications for the GaitShoe, one of which is to allow people to be monitored in a home-environment, unaffected by laboratory settings[2]. This is where the current project continues.

1.2.Objectives

This project will look at the implementation possibilities of a GaitShoe for a home-environment. To be able to design for a more specific target-group, some preliminary research has been done. Initial literature research shows that Parkinson's Disease (*PD*) patients could benefit from the GaitShoe concept.

At the moment, PD patients with an early stage of PD are able to perform daily tasks, but are faced with their reduced abilities everyday. Furthermore, though PD patients can live independently at home, they have to pay regular visits to physical therapists for check-ups and exercises.

The goal of the current product concept, SensorShoe from now on, is to offer mobile real-time gait analysis for PD patients, and remote monitoring and control by caregivers. The summarised objectives are listed below.

1. Provide PD patients with an easy to use mobile gait analysis device
    1. Enhance daily life of PD patients
    2. Improve independence of PD patients
2. Provide caregivers with an effective remote monitoring and control tool for PD patients
    1. Save time of caregivers

1 *See http://www.media.mit.edu/resenv/GaitShoe/index.html*
2 *S.J. Morris, 2004*

1.3.Focus of this Study

The detailed design of the sensors on the shoe has already been described in the GaitShoe project, as mentioned in the previous paragraph. This project will focus on the *human-machine interaction* between the SensorShoe and the PD patient. Together with the detailed design of the shoe sensors this should result in a feasible integrated SensorShoe concept.

Assumptions / Limitation

- We assume the SensorShoe to operate with accelerometers and gyroscopes:
  - 3 axis of accelerometers; x,y,z
  - 2 axis of gyroscopes; x,y
- The analysis and processing of raw sensor data is beyond the scope of this study

1.4.Approach

The following approach is used, based on the general approach for user interface design[3].

1. Perform a small-scale literature research on Parkinson's Disease and Gait Analysis technology, to explore these fields of science.
2. Use the results of the literature research to define a user and a use scenario
3. Determine the core system functions and requirements. In other words, describe what the system should do and how the user interface should support this.
4. Develop interface concepts according to requirements.
5. Test interface concepts, by conducting heuristic evaluations.
3. Based on the results of the heuristic evaluations, one interface concept will be developed in to a functional prototype, which may later be used for testing.

Result

The research will result in an interface design and prototype for the SensorShoe, aimed at PD patients.

Because of time limitations, the prototype will not be fully functional. Furthermore, usability testing will not be conducted within this research. However, several recommendations can be given afterwards, with respect to further development.

3 *Stone et al, 2005*

2.Literature Research

To introduce the context of the development of the SensorShoe, this chapter will start with an introduction about Parkinson's Disease and PD patients. The effects of the disease will be described, followed by the problems PD patients have to deal with.

Next, the possibilities of current gait analysis methods are investigated. The results of these investigations provide a starting point for the rest of the SensorShoe development.

2.1.Parkinson’s Disease

James Parkinson first described the disease in 1817 as “shaking palsy”[4]. It was only in 1960s that scientists discovered that this disease was caused by a loss of brain cells which produce dopamine.

Parkinsonism was defined as the motor aspects of PD, this report will mainly focus on this part of PD.

– PD is most common with European people, it’s much less common with Africans[5]. East Asian people have an intermediate risk. In rural areas there are more people with PD then in the urban area’s. Generally, more men are PD patients then women.

– In the USA one million[6] people suffering from PD and about 40.000 thousand people are diagnosed with PD each year. This is between 100 and 250 per 100.000 US citizens. In China this number is around 1700 per 100.000 for those older then 65 years[7]. In average 14.8 people per 100.000 in Finland have PD.

– It’s not common to have PD for people under 40 year, though it is possible. Generally, the symptoms are beginning around the age of 58-60 (in the USA).The symptoms increase as the age increases, however, around 15% of the PD patients are diagnosed before 50 years.

Causes

Parkinson’s disease is a failing or braking down of brain cells which results in a loss of dopamine-production[3,5]. The failing brain cells are located in the substantia nigra, which is an area in the brain. Dopamine is a chemical which is a messenger for neurological signals; the signals mainly consist of information for controlling the movement of a body.

Symptoms

Common symptoms of PD are[8]:

- Tremors of the limbs, jaw and face. The shaking of the body parts is uncontrollable [2], which makes daily tasks more difficult. Even though this is the most well-known symptom, just 30% [3] of all PD patients experience tremors.
- Rigidity, an abnormal stiffness of the muscles, of the limbs and trunk. This causes an increased risk for falling.
- Bradykinesia. All movements become very slow; the walking speed decreases and one starts to shuffle. This symptom is considered to be the most disabling of PD.
- Postural instability causes PD patients to fall. The instability is caused by loss of balance and coordination.

4 *Langston, J.W., 2006*
5 *See http://en.Wikipedia.org/wiki/Parkinson’s_disease, consulted on 22-3-2007*
6 *The Frequently-Asked Questions about Parkinson’s Disease. New York, USA: Parkinson’s Disease Foundation, 2006*
7 *See http://en.Wikipedia.org/wiki/Parkinson’s_disease, consulted on 22-3-2007*
8 *See www.pdf.org, consulted on 22-3-2007*

These symptoms may result in the following gait-related disorders:[5]

- Short steps
- Shuffling gait (festination)
- Freezing (difficulty initiating gait)
- Difficulty to turn
- Loss of balance

In general, it can be said that PD patients suffer of a decreased quality of life, since they are often not able to perform daily tasks. Even small tasks can be difficult, such as getting out of bed.

Treatments

Medication

The purpose of medication for PD is bipartite.

First, medication can increase the levels of dopamine in the brains, secondly, the medication can help getting the dopamine absorbed by the body. Levodopa (or L-dopa, a dopamine increasing medicine) is most commonly used, 70 to 80% of the PD patients use Levodopa. Several other types of medication are used at the same time to be able to reduce the symptoms of PD.

A medication which is used combined with Levodopa is Carbidopa; this is a medicine which is from the second category. By using Carbidopa, more of the Levodopa is transported to the brain instead of being used in the bloodstream. This results in a lower required dosage of Levodopa.

Surgery

Generally there are three kinds of surgery which are used to decrease the effects of PD. Firstly, Pallidotomy which relieves rigidity and bradykinesia. Secondly, Thalamotomy that relieves tremors. In both procedures, some regions of the brain are destroyed to decrease the symptoms. The third surgery method is to place implants (electrodes) in the brain, which will generate electric impulses to decrease the symptoms.

Therapy

Regular exercise is important for PD patients. With exercise the muscles are trained. The muscle strength is maintained and therefore the mobility, flexibility, balance, range of motion etc is maintained as well.

Besides regular exercise, different therapies exist. All these therapies help to control the symptoms of PD and make daily life easier. Physical therapy helps, just like daily exercise, to maintain muscle strength. Speech therapy helps increasing the voice volume and makes talking more easy. Occupational therapy helps PD patients find other ways in doing their daily tasks which are difficult to perform.

2.2.Gait Analysis

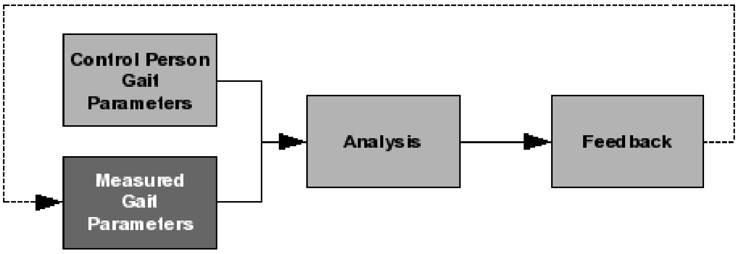
The above paragraph already mentioned problems with walking caused by reduced muscle control. Physical therapy can be used to teach the patient how to cope with these problems. At home, patients can do regular exercises to keep their muscles in shape. Furthermore, the effects of medication and therapy can be evaluated by a physical therapist, using so called gait analysis systems.

Fig. 2: Test person in a current gait analysis laboratory

Gait analysis is primarily used as an objective and quantitative method to record the effectiveness of physical therapy. it is a method of recording the way people are walking in many different ways. During the gait analysis, three characteristics are measured: the temporal, kinetic and kinematic aspects of the gait[9].

- Temporal characteristics, often also seen as kinetic aspects[10], are the characteristics which often change during therapy. They are easy to measure and should often be measured. Examples of temporal characteristics are stride length, cadence and velocity.
- Kinetic characteristics exist of gait which is caused by external forces. These forces can be caused by the ground or forces acting on the PD patient. Important is the pressure carried out on the ground and thus the force on the knee.
- Kinematic characteristics include the movement of the body itself, important examples are the linear and angular displacements, velocities and acceleration.

The diagram below shows the basic structure of a gait analysis. The PD patient is being watched by the gait analysis system (for example by video camera's or body sensors) while performing an exercise, such as walking. By comparing the gait parameters of the PD patient with the parameters of a healthy age-matched control person, the gait analysis results in a certain type of feedback.



The feedback could be 'increase your stride length' or 'change walking rhythm'. There are different ways of sending this feedback to the PD patient. If the goal of the gait analysis is to evaluate the performance of a patient, feedback is not given at all.

9 *Melnick, M.E. et al. 2002*
10 *Peppe, A. et al. 2007*

2.3.Gait Feedback Cues

Several sources indicate that feedback cues could help the patient with improving their stride length, cadence and other important gait parameters. Research has been done to determine which types of feedback can be used, and how effective they are. This paragraph lists several of these feedback methods, along with their supporting research and an indication of effectiveness.

Visual Cues

Several studies investigated the effect of visual cues on a patient's gait[11], [12]. A study of Martin[13], it was found that the stride length of PD patients could be increased by using visual cues perpendicular to the walking path.

Continued research, for example that of Morris, further explored the possibilities of visual feedback. it is shown that visual markers (SL markers) can increase the walking velocity of PD patients by increasing their striding length. In the same experiment, the use of a subject mounted lighting device (SMLD) caused similar improvements.

	Baseline		SL markers		SMLD	
	Patient	Control	Patient	Control	Patient	Control
n	14	14	14	14	13	14
Velocity (m/s)	1.06 ± 0.21	1.39 ± 0.22	1.17 ± 0.18	1.36 ± 0.17	1.22 ± 0.19	1.41 ± 0.24
Cadence (steps/min)	120 ± 11.0	117 ± 8.0	105 ± 14.1	120 ± 11.7	112 ± 11.7	113 ± 12.9
Stride length (m)	1.10 ± 0.25	1.42 ± 0.18	1.34 ± 0.09	1.36 ± 0.07	1.29 ± 0.20	1.49 ± 0.17

Fig. 1: Results of the visual feedback experiment (From Morris, 2001)

Current research is working on an explanation for the effects of visual cues. No hard evidence is given yet, but one theory says it may be due to the concious awareness of the movements that's provided by the visual cues[14]. Being able to see the movement could make it easier to actually carry out the movement. This theory could also apply to the other feedback modalities.

Fig. 2: Test person equiped with a SMLD

While the above research primarily used directional cues (stripes), another study used rhythmic visual cues to affect the gait rhythm of the patient[15]. This form of feedback appears to be effective as well, but has some drawbacks. Visual cues are disturbing for the environment of the patient, and other sources of light may disturb the rhythm.

Another development in this area is the use of *virtual reality*. By projecting objects on a virtual field of vision, a patient is able to improve his/her gait. At the moment only short-term effects are found. Further research should indicate the possibilities of Virtual Reality for long-term effects.

11 *Lewis et al, 2000*
12 *Morris et al, 2001*
13 *Martin JP, 1967.*
14 *Morris et al, 2001*
15 *van Wegen et al. 2006*

Audio Cues

Auditory feedback can be used in several ways. First of all, users can be given spoken clues about their gait. For example, a simple command of 'walk towards the door' can help the PD patient in fulfilling this task. Spoken information about the walking speed and distance may also help.

A second way of using auditory feedback is to provide the user with rhythmic audio cues, or even music. As walking is quite a rhythmic process, the presence of a stable rhythm is proven to be helpful for PD patients' gait. An example of such auditory feedback can be found in the GaitShoe project[16].

Auditory feedback can be provided through headphones, which prevent the user from annoying or disturbing the environment. However, headphones may damage the ears, and don't allow the user to receive the audio feedback while listening to others or while participating in traffic.

Somatosensory Cues

To solve the mentioned shortcomings of auditory feedback, some research has also been done in the field of tactile or *somatosensory* feedback. This feedback uses the skin to communicate with the user, by applying movement, deformations or pressure to the skin. This feedback can be used for rhythmic feedback, but may also provide directional information (i.e. left/right directions).

Experiments have been conducted to investigate the relation between somatosensory feedback and possible interference with visual feedback[17]. Feedback was given using an RSC (A vibrating device which was held by the test persons) and visual feedback, by providing the test persons with a virtual corridor projected on a screen while walking. The results are shown in the diagram below.

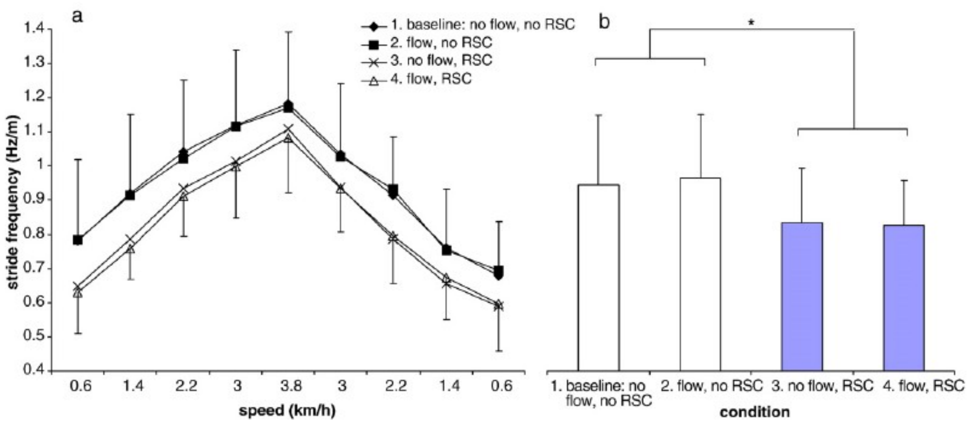


Fig. 3: Results of the somatosensory feedback experiment (From Wegen et al, 2006)

The results lead to the conclusion that somatosensory feedback has about the same effect as audio feedback, and could therefore be seen as a feasible alternative. Furthermore, it is concluded that the somatosensory feedback is not affected by the visual cues, which allows multi-modal feedback as well.

The major advantage of somatosensory feedback is that it can be sent to the user discretely, without anyone noticing it. This aspect should be taken in to account during the further design of the SensorShoe.

16 *Morris et al, 2001*
17 *van Wegen et al, 2006*

2.4.Conclusions

This chapter started with a review of Parkinson's Disease (PD). PD is a disease that causes failure of braincells, resulting in a reduced dopamine production. In turn, this results in several symptoms, including loss of limb control, stiffness and tremor of muscles. Treatments are available, but can not yet cure the disease entirely. It was found that physical therapy plays an important role in controlling the disease and reducing the effects.

The next part of the literature research investigated the possibilities of gait analysis methods for PD patients. Several studies have already indicated that laboratory-based gait analysis can help PD patients by providing them with feedback on their gait. The gait-related feedback, or gait cues, can be provided in different ways. These have been further investigated and described.

Research shows that feedback cues, being visual, audio or tactile, can significantly improve the gait of PD patients. An overview of advantages and disadvantages of these techniques has been presented, which indicates that the functional use of each method is equal, but the usability of the methods differ.

Visual and audio feedback cues may annoy the environment of the user, while tactile feedback is usually more discrete. This is an important consideration for the further design of the SensorShoe.

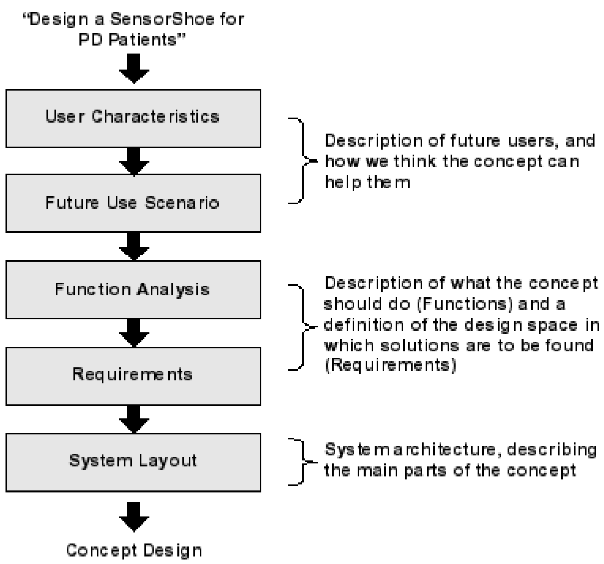
3.Concept Development

The literature research indicates the need for the development of a SensorShoe for PD patients. This chapter describes the development of the SensorShoe concept, which will later be further developed in the Detailed Design chapter.

The diagram below shows the approach that will be used for the concept development. As shown, the first step is to define the target group, including future users and future use of the product, described in a Future Use Scenario.

From this scenario the main functions of the concept will be derived, describing what the concept should do. The requirements will define the design space in which solutions for the functions have to be found. After determining the functions and their requirements, an integrated system layout will be defined, describing the system components and their interactions with each other.

This approach should result in a SensorShoe system concept suiting the needs of our target group.



3.1.User Characteristics

The first step in the concept development phase is the definition of the target group. As said in the introduction, the SensorShoe will be designed for PD patients. However, the PD patient will not be the only end-user of the product.

The caregiver is another important stakeholder. He/she will use the SensorShoe to remotely monitor and help the PD patient. Therefore it is important to also consider the characteristics of the caregiver in this design.

Each of these users is described by the following user characteristics, which are mostly based on information from the literature research of chapter 2.

PD Patient

- Age: mostly 50 and up
- Sex: both male and female
- Motor skills: Limited[18]
  - Slow movements
  - Uncontrollable movements
  - Limited reach of limbs
- Cognitive skills: No specific PD-related limitations, but
  - Decreasing sight and hearing due to ageing
  - Decreasing memory capabilities due to ageing
- Computer experience: limited or none

Caregiver

- Age: 30 to 60
- Sex: both male and female
- Cognitive skills:
  - Assumed to have no cognitive disabilities
  - Medical knowledge
  - Physical knowledge
- Computer experience: daily use of administrative software and home-use
- Limited mobility
- Supervises large patient group

[18] *See paragraph 2.1*

3.2.Use Scenario

it is common for a product design project to ask users what they'd like to see in a product. However, in case of designing new/future products, it is hard for people to imagine what they could do with, or want from such a product. As an alternative to questioning people, it is therefore decided to use a Future Use Scenario.

The scenario describes a future in which the product already exists. The characteristics of the previous paragraph can be used to create *persona's*, which can be placed in to the future use scenario. Imagining the persona's in the future use scenario results in a product description that can be used for further development.

To do so, two persona's will be created first. They represent a future PD patient and a future caregiver. After they've been created they will be placed in to a Future Use Scenario.

Persona's

PD patient - Dirk is a 53 year old man, who lives on his own in a small house. Dirk has been a PD patient for about 10 years now, which causes Dirk to have problems with daily tasks. Most effected are the muscles of his legs, so walking around the house is quite difficult.

Caregiver – Mary is 32 year old physical therapist. She runs a clinic in a medium sized town, where she supervises about 20 PD patients. Dirk is one of these patients. She has regular appointments with the PD patients, but needs time to help other patients as well.

Future Use Scenario

When he awakes, Dirk is already faced with PD. it is hard to get out of bed because his muscles are stiff, and he hasn't taken medication yet So Dirk stumbles towards the bathroom, takes a shower and gets his clothes on. With that, Dirk also puts on his pair of SensorShoes.

Without consciously knowing it, Dirk's gait is being watched and analysed by the SensorShoe. The data is logged and later sent to Dirk's physical therapist.

After breakfast, Dirk decides to do some shopping. The walk to the supermarket used to take him about 5 minutes, but this time increased ever since he got PD. Before Dirk leaves the house, he 'activates' the SensorShoe. This means that the SensorShoe will provide Dirk with real-time feedback on his gait, improving speed and stability.

While the first 10 meters are quite unstable, Dirk notices that by following the feedback cues of the SensorShoe he improves the stability of his gait. After a while he uses the feedback cues on an unconscious attentional level.

In the afternoon, when all the shopping is done, the SensorShoe reminds Dirk of his daily exercises. These exercises help Dirk keeping his muscles in shape, and slow down further PD-related symptoms. The SensorShoe interface informs Dirk about which exercises he should do, and for how long. After finishing the exercises, the results are sent to Dirk's physical therapist, Mary.

Mary receives the daily or weekly log of Dirk's activities. The log indicates which activities have been detected, and how Dirk was supported by cues. For example, the log contains a report of the 15 minutes walk to the supermarket, also reporting the feedback cues that were used. Additionally, the therapist can analyse the effects of the daily exercises on the performance of Dirk.

After analysing these data, Mary can adjust the training programme or feedback cues to optimise the effects for Dirk.

3.3.Functional Analysis

Based on the scenario, a set of functions has been defined which describe the functional behaviour of the system concept. The functions describe *what* the system should do, but do not yet define *how* the system should do this.

– **Analyse Gait** - The main function of the SensorShoe is to measure and analyse the gait of a person with Parkinson's Disease. The gait will be analysed based on the acceleration and gyroscopic changes of the feet. After analysing the raw data three entities should be known: walking speed, cadence and stride length.

– **Provide Real Time Gait Feedback** – The SensorShoe should be able to provide the user with real time feedback on his/her gait. This means that the user should be able to walk with the SensorShoe, while receiving cues on gait improvements.

– **Provide Physical Therapy and Feedback** - The caregiver can make a selection of several exercises which the patient has to do daily. This is the physical therapy which is done at home. The user can receive feedback on these exercises.

– **Evaluate the Feedback** - For a caregiver, it's important to know how a patients experiences the exercises. Based on these evaluations the caregiver can alter the physical therapy exercises to fit the needs and preferences of the patient.

– **Record and send Log to Caregivers** - To know how a patient progresses during the physical therapy, the SensorShoe will record the gait of a patient and send it to the caregiver.

– **Receive PT Settings from Caregivers** - The caregiver receives the information (evaluation and gait analysis) at his office. On his own computer he can interpret the results and adjust the physical therapy. These adjustment need to be send to the SensorShoe.

3.4.System Requirements

As said, the functions only describe the functional behaviour of the system. Technical solutions have to be found for each of these functions, and in the end be integrated in to a final product. To define the design space of the functions, *system requirements* will be used. Requirements indicate limitations and conditions for the functions.

Functional Requirements

Functional requirements define the design space for the functional solutions of the concept. The list below presents requirements for each of the main functions of the SensorShoe.

Analyse Gait

- The SensorShoe must measure the walking speed (m/min)
- The SensorShoe must measure the cadence (steps/min)
- The SensorShoe must measure the stride length (m)
- The SensorShoe must measure the vertical displacement of the foot (mm)

Provide Real Time Gait Feedback

- If desirable the SensorShoe will provide feedback to the user during a walk, this to support the cadence and stride length.
- The user should always be able to turn off and turn on the feedback

Provide Physical Therapy & Feedback

- The SensorShoe helps to remember the user to its daily physical therapy
- The SensorShoe must accompany the user during the physical therapy. (indicate what to do and the amount; when an exercise is not performed right, the SensorShoe should give suggestion how to improve the performance)
- The user should always be able to turn off and turn on the feedback

Evaluate Feedback

- The user should be able to influence the behaviour of the feedback of the SensorShoe
- After the exercise an evaluation can be given by the user. Whether the exercises weren't to fast, to many, to difficult or to easy, to slow or to little. Based on this information, the caregiver can adjust the Physical Therapy.

Record and send Log to Caregivers

- The SensorShoe must measure the progress in every exercise (both PT and walking support)
- The SensorShoe should store the gait data in order to be able to analyse it (pre analyse raw data)
- The SensorShoe must be able to send the raw, and pre analysed, data to the caregiver
- The SensorShoe should also be able to send the users evaluation to the caregiver

Receive PT Settings from Caregivers

- The caregiver must be able to interact with the SensorShoe from a distance
- The caregiver can change the settings of the SensorShoe. The daily Physical Therapy exercises can be adjusted as a result of the gait analysis. The caregiver can change the Physical Therapy content or the amount of it.
- Also, the caregiver must be able to send short text messages to the user, in order to explain the changes in the PT content.

Usability Requirements

Usability requirements define how the user should (be able to) operate the SensorShoe. The following requirements are quite generic, and will be further specified during the detailed design of the SensorShoe.

Interface Usability

- Input and output of the SensorShoe interface should support the capabilities and limitations of the user group
    - Screen output should be readable for our target group
    - Audio output should be receivable for our target group
    - Tactile input should be comfortable

Practical Use

- Since the device is portable, one should be able to carry the device around.
    - The concept should use a (rechargeable) mobile power supply
    - The concept should be as lightweight as possible
    - The concept should be compact
- The user should not feel stigmatised while operating the concept

3.5.System Architecture

With the desired functionality and requirements defined, a system concept can be made. The system concept describes a global system architecture. This architecture should support the functionality and requirements.

System Modules

The global architecture of the system consists of three modules. Each of these modules takes care of one or more functions defined earlier. The following list shows the allocation of functions over the system modules.

- **Sensor-equipped shoe -** This shoe is being developed by another project group and will therefore not be described in detail here.
  - Analyse Gait
- **Interface unit** - The project group prescribes a PDA to be used. The interface for the PDA will be designed and described in detail in the following paragraphs.
  - Provide Physical Therapy and Feedback
  - Evaluate the Feedback
  - Record and send Log to Caregivers
  - Receive PT Settings from Caregivers
- **Feedback unit** - The third part of the architecture consists of a feedback unit. The feedback unit will send the gait cues to the user. As found in the literature research, several types of feedback can be used, including auditory, visual and tactile[19]. These possibilities will be evaluated in the next paragraph, after which a selection can be made that is to be used within this design.
  - Provide Real Time Gait Feedback

[19] *See paragraph 1.4*

3.6.Conclusions

Chapter 3 started with describing the future users of the SensorShoe. Both the patient and the caregiver have been described and were placed in a future use scenario. From the scenario the major functionalities and requirements have been derived. The main functions of the SensorShoe are listed below.

– Analyse Gait
– Provide Real Time Gait Feedback
– Provide Physical Therapy and Feedback
– Evaluate the Feedback
– Record and send Log to Caregivers
– Receive PT Settings from Caregivers

After defining the functions a system architecture has been designed, which should include all of the SensorShoe functions. The architecture consists of three modules, namely the shoe, a feedback device and a PDA. All functions have been allocated to a particular module.

The next chapter will further describe the detailed specifications of these modules, as well as the interactions between the modules.

4.Detailed Design

The previous chapter described the global architecture of the SensorShoe concept. This resulted in a system layout containing three modules, namely the Shoe, the PDA and the Tactile Feedback component. In this chapter each of these modules will be further specified, and integrated in to a final detailed design.

4.1.Modules & Interactions

The interactions between the modules (exchange of information) are to be specified. A data-flow diagram of the entire system has been made, as shown in the diagram below.

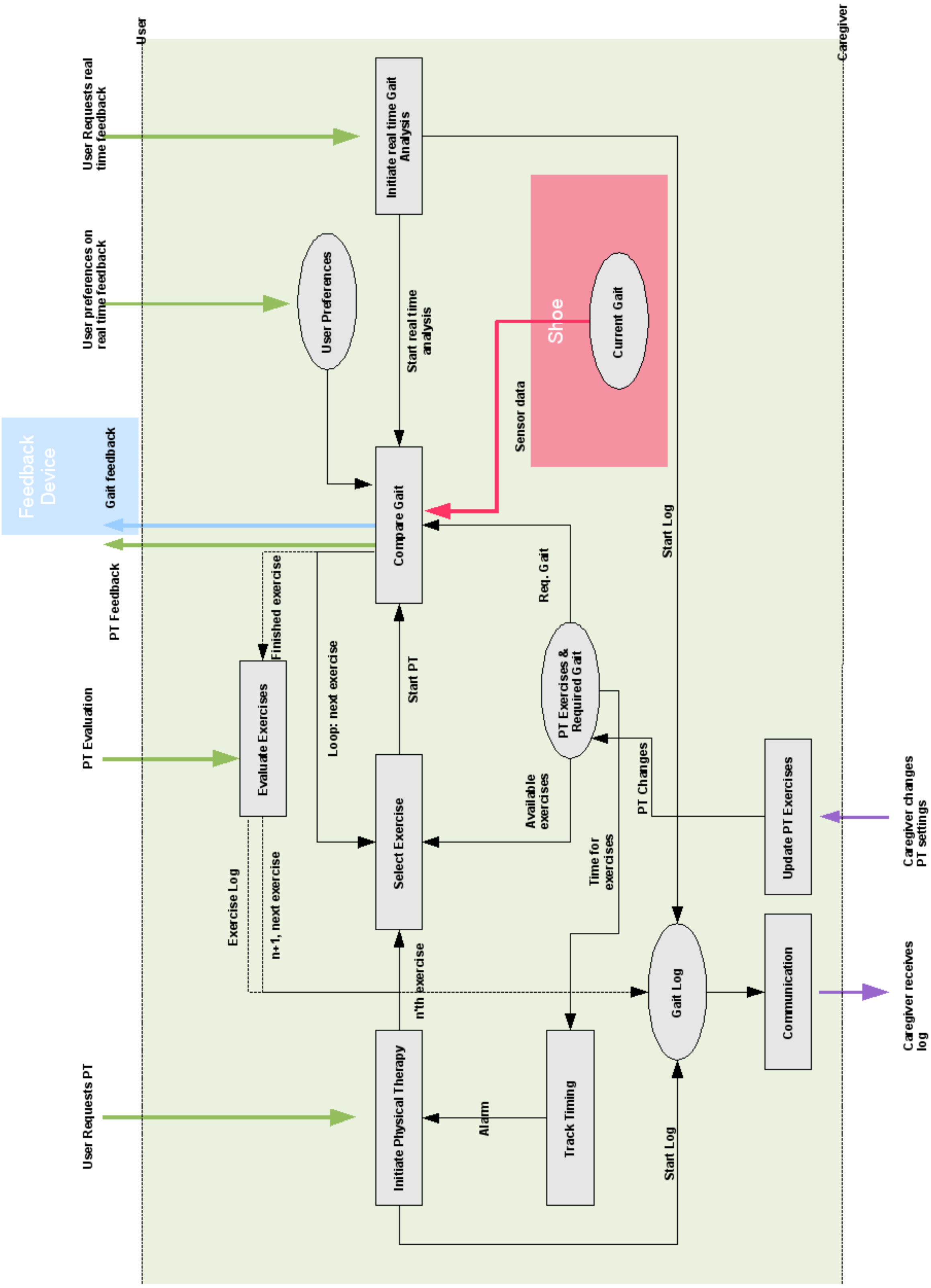
The diagram contains the three modules, indicated by the coloured rectangles. Each module contains functions and data-sets which support the required functionality for each module. For example, the shoe contains the data-set “Current Gait” which provides the PDA with information about the gait of the user.

The diagram also indicates how the modules interact with the user and/or caregiver. The dotted horizontal lines indicate the border between user, caregiver and 'system'. These interactions can be used to design the user interface for the PDA.

The internal functions and data-flows of the system have been colour-coded:

- Green arrows represent data exchange between the PDA and the user
- Blue arrows represent data exchange between the Tactile feedback unit and the user
- Red arrows represent data exchange between the Shoe and the PDA
- Purple arrows represent data exchange between the caregiver and the PDA
- Black arrows represent PDA internal data flow

The data flow diagram can be used for the further implementation of the PDA software. In this study it will be mainly used to specify the interactions between modules, and the interactions between the user and the system.


User
Caregiver
User Requests real time feedback
User preferences on real time feedback
Feedback Device
Gait feedback
PT Feedback
PT Evaluation
User Requests PT
Initiate real time Gait Analysis
User Preferences
Start real time analysis
Shoe
Current Gait
Sensor data
Compare Gait
Start Log
Req. Gait
Finished exercise
Loop: next exercise
Start PT
Evaluate Exercises
PT Exercises & Required Gait
Available exercises
PT Changes
Select Exercise
Update PT Exercises
Caregiver changes PT settings
Time for exercises
Exercise Log
n+1, next exercise
n'th exercise
Gait Log
Communication
Caregiver receives log
Initiate Physical Therapy
Alarm
Track Timing
Start Log

4.2.Shoe Module

Though the shoe and its electronics is being developed by another project group, the required functionality and specifications will be presented here. This should ensure compatibility between the user interface and the shoe.

Sensors

The main function of the shoe is "Analyse Gait"[20]. As mentioned in the first chapter, the Shoe component will use several types of sensors to measure current gait parameters. These sensors include:

– x,y and z accelerometers

– x,y gyroscopic sensors

Comparable accelerometers an gyroscopic sensors have been used in the GaitShoe project. The specifications of those sensors have been used for the further design of the SensorShoe as well. These specifications are available in appendix C.

The sensors will start measuring as soon as the shoe is put on. The main reason for this is that more gait-data results in a more reliable analysis. Furthermore, the shoe will not perform the analysis itself. This would require too much (processing) power. Therefore the data will be sent on a constant interval to the PDA[21]. The required communication for this function is discussed in the next section.

Furthermore the sensors should be power efficient, so that the SensorShoe may be used for a day (24 hours) without recharging. Because the exact sensor specifications are not available for the SensorShoe project yet, it is hard to give precise information about the battery requirements. However, sources indicate that a Lithium-ion Polymer (Li-Polymer) battery provides sufficient power while also offering design flexibility[22].

The shoe module will be equipped with the following components.

Component	Power usage (peak/avg, mW)	Dimensions
Accelerometers [23] ADXL-330	unknown @ 3V	4 mm x 4 mm x 1.5 mm, < 1,0 gr
Gyroscopes[24] IDG-300 2D Gyroscope	unknown @ 3V	5 mm x 5 mm x 1.5 mm, < ~1,0 gr
Bluetooth module	90 / 0.09 mW	-

Communication

To send the sensor output to the PDA, the SensorShoe will use a class 2 Bluetooth connection. Bluetooth offers several advantages[25].

– Low power consumption

– Low-cost chips

– Small and light-weight hardware

– Sufficient bandwidth and range

20 *See Chapter 3*
21 *We assume the analogue data from these sensors to be converted to a signal which can be sent by the the Shoe to the PDA.*
22 *See http://en.wikipedia.org/wiki/Lithium_polymer*
23 *See Appendix C*
24 *See Appendix C*
25 *See http://www.silicon-press.com/briefs/brief.bluetooth/index.html*

Bluetooth has been designed for low-range and low-energy connections. Furthermore, Bluetooth is a common communication method on modern PDA's. Class 2 Bluetooth supports a maximum connection range of 10 metres, with a maximum permitted power of 2.5 mW (4dBm). This class has been chosen because of the range it offers, which should be at least 1 metre (distance between the foot and hand-height).

4.3.PDA Module

The PDA is a major part of this concept. it is decided to use a PDA because of it is relatively cheap, and available for consumers. Furthermore, a PDA offers a development platform for which a scalable user interface can be designed. This paragraph will present detailed specifications and requirements for the PDA, as well as the design of the GUI for this device.

Specifications

The following specifications should be met by the PDA in order to work with the SensorShoe.

- Bluetooth connection, which will be used for communication with the Shoe component and the Tactile Feedback unit.
- Long-life battery, which should allow the PDA to operate (with Bluetooth enabled) for about 24 hours without recharging.
- A visual display with touch screen, with a minimum screen size of 3,5”, which means 71.1 mm x 53.3 mm, and a minimum resolution of 240x320 pixels.
- Support for audio feedback

As an example, we've used the HP iPaq hx2490 PDA[26], which meets these specifications.

Functionality

As defined in chapter 3, the PDA will take care of several important system functions. These functions will be provided to the user trough the graphical user interface of the PDA.

- Provide Physical Therapy and Feedback
- Evaluate the Feedback
- Record and send Log to Caregivers
- Receive PT Settings from Caregivers

The first two functions are most relevant for the patient, while the last two functions are only useful for the caregiver. The focus of this project is on the design of the PDA GUI for the patient.

GUI Structure

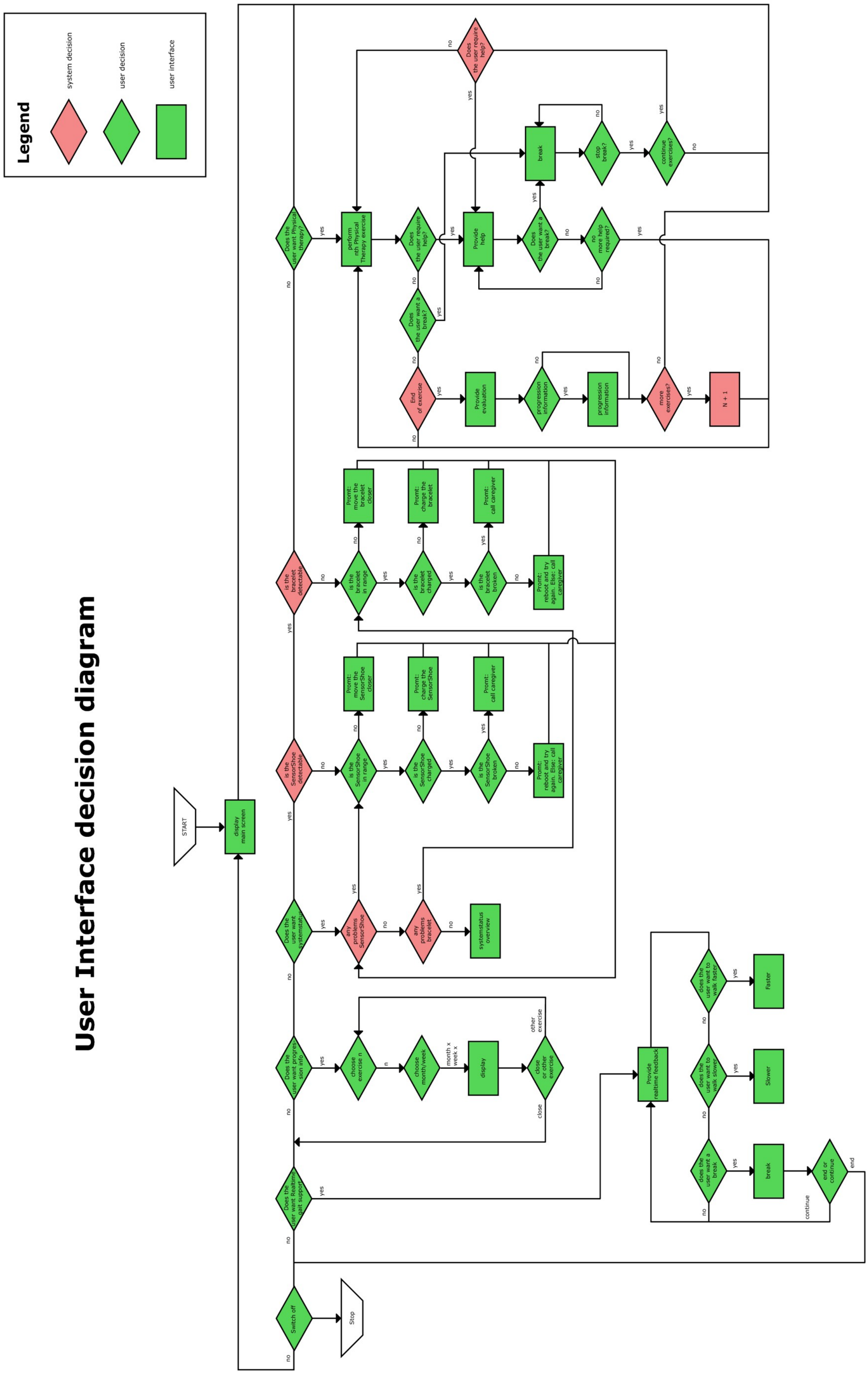
The design of the GUI starts with defining the structure of the interface. This structure is shown in the Decision Diagram below. The diagram starts with the 'main screen' of the interface, from which the user can choose an option. These options provide access to the main functions of the PDA:

1. Start Physical Therapy Session
2. Start Real Time Gait Analysis
3. View Patient Progression
4. Check System Status

Each option provides the user with new choices, as presented in the diagram. This diagram can be used to see which items should be available in which parts of the interface.

[26] *See http://www.pdashop.nl/product/19068/hp-ipaq-hx2490.html#specificaties*

User Interface decision diagram



Interface Concepts

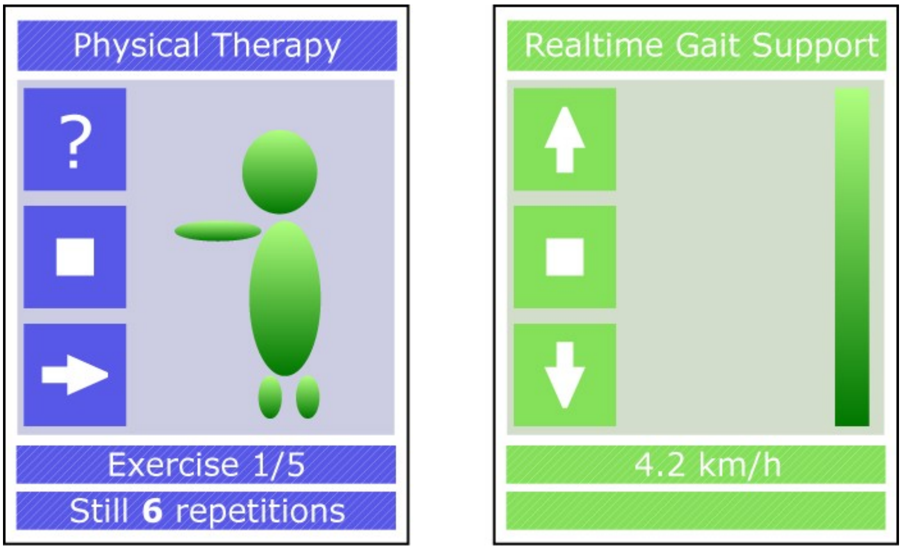
Having defined the GUI structure, the actual interface screens can be designed. These design concepts consists of some sample screens, presenting a concept layout and widgets. The concepts differ in user approach, usability and 'look and feel'. After presenting these concepts, a heuristic evaluation will be used to evaluate the concepts, and decide which of them is feasible enough to further develop.

Concept 1

Concept 1 is the most 'standard' design of all five. The header tells the user which function is used (Physical Therapy, Real-time gait etc.). The footer gives the user extra information:

- how many exercises still to go?
- How many repetitions?

The three buttons on the left are the choices the user has: i.e. pause exercise, help or next. With Real-time gait the user can increase or decrease the feedback of the walking speed. Different background colours indicate different functions.

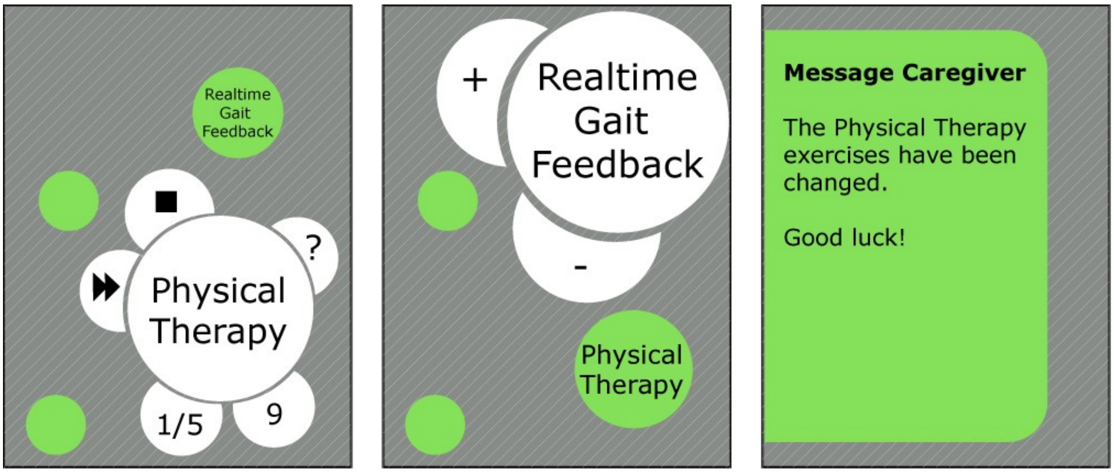


Concept 2

The second concept is a less conservative concept. This concept is based on a flower. For a flower it is important to attract bees to the core of the flower. The most important part is played by the leaves, which lure the bees to the flower.

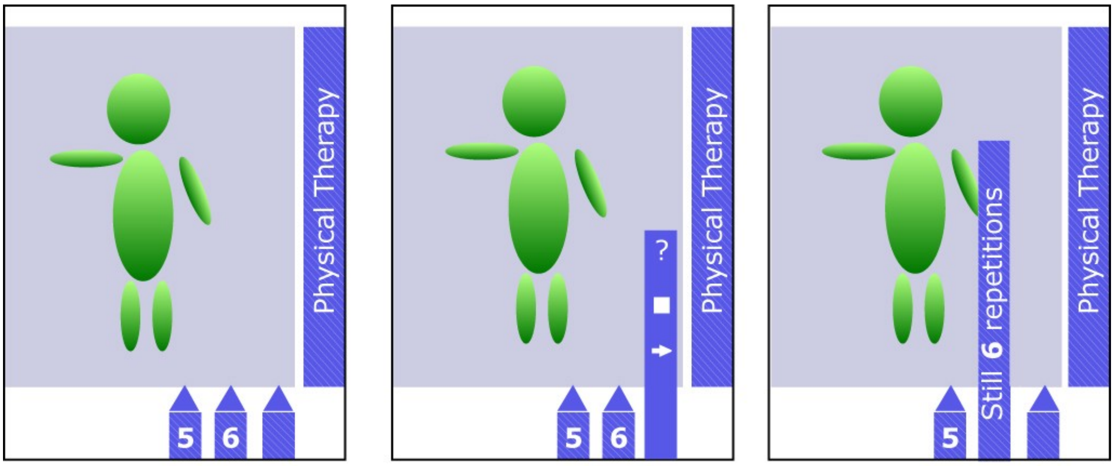
In this interface flower leaves play an important role as well. The leaves hold the main menu item, and organize them in a natural sense. Each leave contributes in order for the core to be at its best. That's not only in nature, but also appropriate for the interface. Without the menu leaves the core would be useless.

Four circles indicate the four functions. When the user presses a circle, the function is selected. The other three circles move to the background. The selected function blooms: the buttons appear.



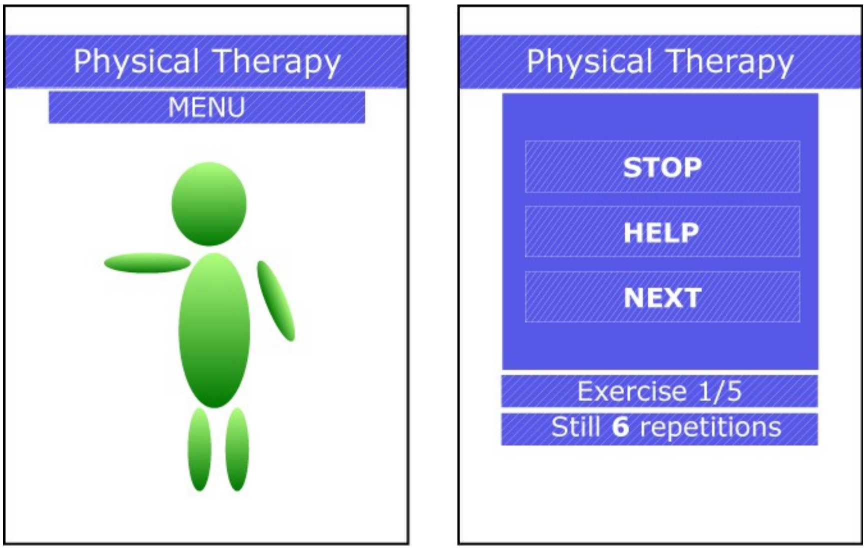
Concept 3

In concept 3 the header is placed on the right. The user can see which function is activated. At the bottom of the interface, three buttons, with triangle shapes on top, are located. Each of them expand when pressed. When expanded, it provides the user extra information, or extra buttons, which are also described in concept 1.



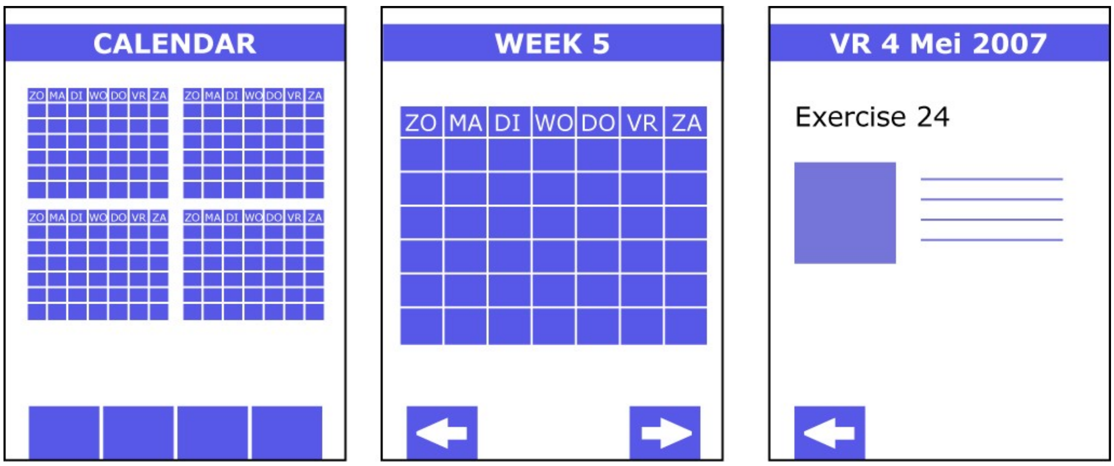
Concept 4

Concept 4 uses a drop down menu. When the menu button is pressed, it drops down over the current used function. This drop down menu provides extra information as well as extra buttons.



Concept 5

This concept is based on a calendar. The user chooses a week and a day. This day contains several exercises which are explain in the next screen. Located at the bottom are several buttons. The header tells the users which function is currently activated.



Concept Evaluation & Selection

The concepts presented above have been evaluated using existing guidelines for GUI design[27]. These guidelines apply to the design for disabled users, general GUI's and website-design. Irrelevant guidelines have been left out. Each concept scored a certain amount of points for each guidelines, resulting in the total scores presented in the table below[28].

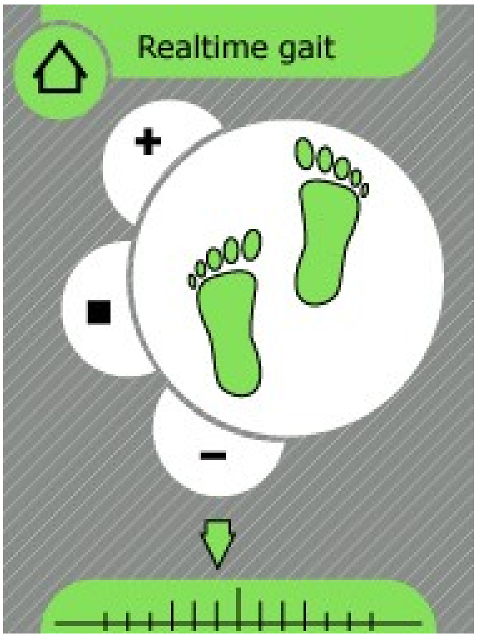
	Concept 1		Concept 2		Concept 3		Concept 4		Concept 5	
	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
Guidelines GUI	23	13	30	9	12	14	23	8	17	14
Guidelines website	6	2	10	2	4	3	7	3	9	2
Guideline disability	7	0	8	0	3	0	7	0	5	0
Sub total	36	15	48	11	19	17	37	11	31	16
Inc. potential	51		59		36		48		47	

Based on the scores, it is concluded that concept 2 meets most guidelines and offers the best potential to improve current design flaws. Concept 2 is further developed using a functional prototype, which in turn will be used for a usability test. The results of this test should indicate whether the concept interface works or not, and which aspects need further improvements.

27 *See paragraph 1 of Appendix B for an overview of guidelines used*
28 *Detailed evaluation scores have been included in paragraph 2 of Appendix B*

Detailed Interface Design

In the previous paragraph the concept designs were evaluated according to the guidelines. Since each concept had its positive features and the concept design is not fully worked out, the positive features of both will be combined. The following sections describe some of the major parts of the final interface. Other parts are shown in Appendix D.

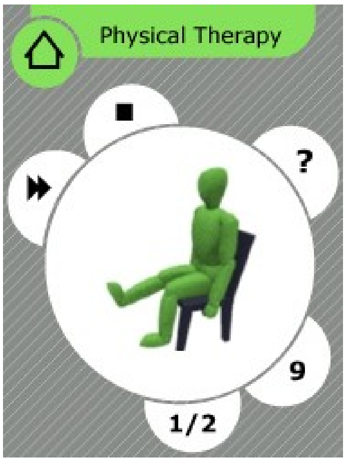


Main Screen

The picture on the left in the above table shows the main screen. The launchpad contains of five buttons, of which four are the main features. The large buttons are the most important features, Physical Therapy and Real time gait support, and the smaller buttons are the more advanced features, system status and progression information. The fifth is the shut-down button. The colours and styling have been chosen in order to create a playful yet serious interface.

Real Time Gait Support

The above screen on the right represents the real time gait support. In this screen one can see the speed of the tactile feedback. In the below part, the arrow points to the current speed. The care giver can pre-set a speed, which is represented by the largest line below. The user can adjust the speed with the "+" and the "-" symbol. The arrow will move as well. When one wants a break, he can press the stop (the square) button, and the tactile feedback will stop.



Physical Therapy

The Physical Therapy has five main buttons. These are located around the picture of the exercise. These are: forward (the following exercise), stop (the pause the exercise), help (the question mark icon, this provides an audio support, as well as an animation of the exercise), "1/2" (one out of two, this tells the user which exercise he is performing) and "9" (this tell the user how many repetitions he still has to do).

4.4.Feedback Module

The main function of the feedback unit is to provide the patient with Real-Time feedback on his gait. For the detailed design of this module, the following questions are to be answered.

- Which feedback modality should be used?
- How can the modality be implemented in the SensorShoe design?

Feedback Requirements

The literature research indicated no major drawbacks or advantages for any of the feedback methods[29]. To select one of the modalities however, a set requirements for the modality has been made.

1. The modality should provide effective feedback
2. The modality should not be stigmatising
3. The modality should be implementable in the SensorShoe architecture;
    1. The modality should be wearable
    2. The modality should be power efficient

Within these limits, available feedback modalities have been listed and evaluated. These are presented in Appendix A. Pro's and con's of each implementation have been included. After presenting the possible solutions, a selection can be made.

For this selection, it was found most important for the user to be able to receive feedback in a non-intrusive way. The visual feedback method doesn't meet this requirement, as it sends out visual cues to the user and his/her environment. Auditory cues trough earphones are more discreet, but prevent the user from interacting with the environment. These considerations lead to the decision to use tactile feedback.

Tactile Feedback

Tactile feedback can be provided without non-users noticing it, and several studies have proven the effectiveness of this method. The detailed design of a tactile feedback unit will be presented in the next chapter.

Tactile feedback relies on the ability of the user to sense tactile signals (for example vibrations) trough their skin. As shown in the diagram[30], the skin consists of two layers (the Dermis and the Epidermis), and contains several types of nerve endings:

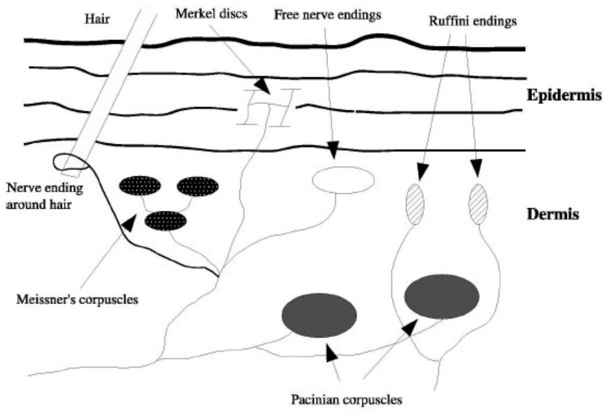


Fig. 4: Schematic representation of the skin

- *Thermoreceptors* sense temperatures and changes of temperature.
- *Noiceptors* sense damaging effects, such as intense heat or high pressure.
- *Mechanoreceptors* sense indentations (pressings), and can be divided in to slowly adapting mechanoreceptors (SA) and rapidly adapting mechanoreceptors (RA). *Merkel's disks* and *Ruffini endings* are examples of SA mechanoreceptors. *Meissner's corpuscles* and *Pacinian corpuscles* are RA mechanoreceptors.

Tactile feedback systems stimulate one or more of these nerves.

[29] *See Chapter 2 for an overview of feedback methods*
[30] *T. Jyrinki, "Perception of Small Device Vibration Characteristics - Test Facilities Setup and Study"*

For example, electro-tactile displays use small electrodes placed on the skin to send electronic signals. The effectiveness of electronic signals depends on the humidity of the skin, the affected area and the applied pressure. This is why it is hard for electro-tactile techniques to become commercially attractive; they're very dependant on individual preferences.

An alternative to electro-tactile techniques are called 'mechanical actuators'. Mechanical actuators physically affect the skin, either by higher frequency (vibration) or lower frequency (pressure, deformations) signals.

– Vibrations should be below 1000 Hz, which is the sensitivity limit for the human skin. A sensitivity peak is found around 250 Hz. Besides the frequency, the sensitivity for vibrations is also affected by the density of nerves in the skin. The skin in the face, tongue and hands is most sensitive[31].
– Lower frequency signals should be within 20-40 kPa[32], which is the range in which pressure is best perceived by the user.

For the SensorShoe it is decided not to use electro-tactile feedback because of the drawbacks mentioned. As the SensorShoe will be used by patients at home we do not want to run the risk of letting these these users hurt themselves because of wrong settings.

Therefore, the SensorShoe will use mechanical actuators to provide the user with rhythmic cues as gait assistance.

Mechanical Actuators

Several technologies are available to enable mechanical tactile feedback. The following table showsthe advantages and disadvantages of the available techniques[33].

Technology	Description	Advantages	Disadvantages
Electromagnetic Motors	Electromagnetic motors produce torque with two time-varying magnetic fields, caused by two coils or a coil and a magnet	- Easy to control - Clean, quiet - Easy design and installation	- Heavy components - Low power densities at small scales - Heat dissipation problems - Low static force capability
Hydraulics	A hydraulic fluid is pressurized by a power plant, controlled by servo-valves and delivered to rotary or linear actuators through pressurized fluid lines	- Force capability, - power output, - stiffness, and - bandwidth unmatched by other technologies	- High mass - Tendency for fluid leaks - Design difficulty - Expensive
Pneumatics	A gas (normally air) is pressurized by a power plant, controlled by servo-valves, and delivered to rotary or linear actuators through pressurized fluid (air) lines	- Good static force capability - Lighter than hydraulics - Pneumatic power plants and distribution systems easier to manage than hydraulics	- Relatively low bandwidth - Low actuation stiffness - Low power capability

31 *T. Jyrinki, 2004*
32 *See http://www.e-skin.ch*
33 *Hasser, 1995, 1996*

Technology	Description	Advantages	Disadvantages
Piezoelectric	Piezoelectric motors translate the vibration of piezoelectric materials to linear or rotary motion using frictional forces to produce usable torques or forces at low speeds, without the need for gear reduction.	-High forces at low speeds in small package - Very small components	- Requires precision machining - Necessary power gating can cause annoying and potentially hazardous noise, depending on the design
Magneto restrictive	Magneto restrictive materials change shape when subjected to magnetic fields. Magneto restrictive motors also mechanically rectify small oscillatory motions of the driving element(s).	- High forces at low speeds in small package	- Necessary power gating can cause annoying and potentially hazardous noise, depending on the design - Heat dissipation can be a problem - Requires precision machining
Shape Memory Alloy	SMA wires and springs contract when heated and expand again as they cool under stress.	- Good power-to-mass ratio - Low efficiency during contraction	- Heat dissipation problems limit relaxation rate of wires - Limited bandwidth

Practical requirements such as lightweight and portability cause the pneumatic and hydraulic solutions to be not-feasible. Using a gas or fluid in a device like the SensorShoe also increases the chance of system failures, and require more maintenance.

The remaining technologies have comparable advantages and disadvantages.

Piëzo actuators are already being used in PDA's and other computer-related hardware to enable tactile feedback. These actuators are able to produce vibrations within 200 to 250 Hz, using less power compared to electro mechanical motors.

Similar projects, such as "Tactile Vest"[34] and "ActiveBelt"[35], use electro mechanical motors for tactile feedback. Though the vibration frequencies are outside the optimum scope of human skin, they've been reported to work for tactile-feedback tasks.

Primarily based on the reports of successful use of electro mechanical motors, it is decided to use these actuators in the SensorShoe as well.

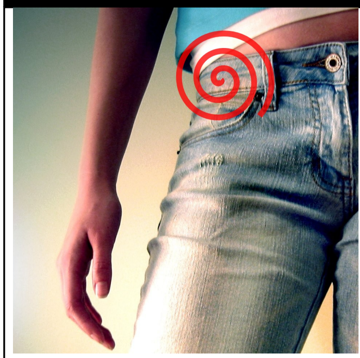
34 *L. Jones et al*
35 *K. Tsukada et al,2004*

Actuator Implementation

One of the major advantages of using electromagnetic motors for tactile feedback is that these motors are small enough to be integrated in to existing products. This should prevent a stigmatising effect of the SensorShoe; other people can't see whether someone is using or wearing the SensorShoe components.

Several possible integrations into existing products have been investigated. They are presented and discussed in the table below.

Ring	Pro's	Con's
	The device can be in any shape, so the personal likings can be a factor in choosing the product.	The technique (for taps and communication) should be very small to be able to fit into a ring. When this is even possible, it will be very expensive.
		The fact that it is possible in any shape makes it also difficult to produce. The product show be individually changed, which makes it more expensive to product.

Belt	Pro's	Con's
	No one notices that the user is wearing an extended belt, since no one can even see the belt.	Since the belt is no directly placed on the body of the user, the pants will reduce the signal strength. Therefore it can be possible that the user will not notice the taps correctly.

Watch	Pro's	Con's
	Almost everybody wears a watch, so no one will notice the user wearing a rhythmic tap device.	For every user, a watch should be made with a different look and feel. Personal taste is of great deal. This diversity causes a more expensive product.

Bracelet	Pro's	Con's
	The bracelet can be hidden under the clothes. As can a watch, but this bracelet does not need to replace the watch and does therefore not need to meet personal preferences (functions etc)	
	A arm/wrist is the best location to use tactile feedback, it's the most sensitive place.	

Clothes	Pro's	Con's
	The actuators can be used wherever a user is most sensitive. The user will not miss any cues.	In order to maintain the right strength of the feedback, the clothes need to be tight. This can be very unconvertible for the user (i.e. hot summer days)
	The clothes can be made in any shape or worn under another set of clothes, in order to hide the technology.	Also with this solution, the product needs to change for every user. I.e. everybody has another size.

Hat	Pro's	Con's
	Since the rhythmic tap device is inside the hat, no one will know that the user is wearing a special hat.	Not everybody likes to wear a hat, this might be very annoying for the user.
		The actuator signal may lose strength since the signal needs to pass the hair.

After reviewing the concept solutions, it is decided to use the bracelet as a platform for the tactile feedback unit. The advantages of this solution are:

- A bracelet is small, and can be worn under clothes. They can easily be designed for different users, for example male/female or young/old
- No adaptations to or additions on existing clothes or accessories are needed
- A bracelet offers sufficient space for a power source and mechanical actuators
- A bracelet is worn on a sensitive part of the body (lower arms)

4.5. Conclusions

The above paragraphs further specified the components of the SensorShoe concept. The shoe, the PDA and the tactile feedback unit have been fully defined, and result in the total SensorShoe concept.

The shoe component has been only been specified in terms of required functionality and specifications. The main reason for this is that the shoe is being developed by another project team. The design of sensors and data analysis methods is beyond the scope of this research.

The PDA component has been specified in terms of required specifications. A specific type of PDA is proposed, which will also be used for further interface testing. A GUI for this PDA has also been designed. Several concepts have been presented, after which one of them is selected for further development and testing, based on a heuristic evaluations.

Required specifications and technology for the tactile feedback unit have also been investigated, which lead to the use of a micro-vibration mechanical actuator. The mechanical actuator can be implemented in a bracelet.

As a result, the SensorShoe offers the user a practical and usable tool for real-time gait analysis and physical therapy assistance. The components use available technology, and have been designed in such a way that they can be used discretely.

5.Evaluation & Recommendations

This report focussed on the user-interface of the SensorShoe project. Other components, such as the sensors for the shoe, are being developed by other project groups. To support integration of the different sub projects, this chapter will look at future work and recommendations for the further development and implementation of the user interface.

5.1.Evaluation

A first short evaluation of the presented SensorShoe concept is done using the system requirements. The following table shows a review of the requirements. The 'fulfilled' column indicates the status of a requirements, which can be 'x' for fulfilled, '-' for not-fulfilled or 'o' for 'fulfilled, but room for improvement'.

Requirement	Fulfilled?	Remarks
Analyse Gait		
The SensorShoe must measure the walking speed (m/min)	x	
The SensorShoe must measure the cadence (steps/min)	x	
The SensorShoe must measure the stride length (m)	x	
Provide Real Time Gait Feedback		
If desirable the SensorShoe will provide feedback to the user during a walk.	x	
The user should always be able to turn off and turn on the feedback	x	
Provide Physical Therapy & Feedback		
The SensorShoe helps to remember the user to its daily physical therapy	x	
The SensorShoe must accompany the user during the physical therapy.	o	The understandability of the physical therapy feedback should be tested
The user should always be able to turn off and turn on the feedback	x	

Requirement	Fulfilled?	Remarks
Evaluate Feedback		
The user should be able to influence the behaviour of the feedback of the SensorShoe	x	
After the exercise an evaluation can be given by the user.	x	
Record and send Log to Caregivers		
The SensorShoe must measure the progress in every exercise (both PT and walking support)	x	
The SensorShoe should store the gait data in order to be able to analyse it (pre analyse raw data)	o	Further development of the analysis software is required for implementation
The SensorShoe must be able to send the raw, and pre analysed, data to the caregiver	o	The communication between the PDA and the caregiver has not been designed in detail yet
The SensorShoe should also be able to send the users evaluation to the caregiver	o	Option is available in the GUI, but communication between the PDA and the caregiver has not been designed in detail yet
Receive PT Settings from Caregivers		
The caregiver must be able to interact with the SensorShoe from a distance	o	The communication between the PDA and the caregiver has not been designed in detail yet
The caregiver can change the settings of the SensorShoe.	o	Option is in the GUI, but the communication between the PDA and the caregiver has not been designed in detail yet
The caregiver must be able to send short text messages to the user, in order to explain the changes in the PT content.	o	Option is in the GUI, but the communication between the PDA and the caregiver has not been designed in detail yet. The caregiver should also be provided with a special GUI for sending messages, PT changes and analysing patient performance.

Requirement	Fulfilled?	Remarks
Interface Usability		
Screen output should be readable for our target group	o	GUI design is based on guidelines, but requires a usability test for more reliable conclusions
Audio output should be receivable for our target group	o	GUI design is based on guidelines, but requires a usability test for more reliable conclusions
Tactile input should be comfortable	o	Requires a usability test for more reliable conclusions
Practical Use		
The concept should be as lightweight as possible	o	More details on electronic components can be used to get a more reliable estimation of concept weight ans power usage
The concept should use a (rechargeable) mobile power supply	o	More details on electronic components can be used to get a more reliable estimation of concept weight ans power usage
The concept should be compact		
The user should not feel stigmatised while operating the concept	o	Requires a usability test for more reliable conclusions

The requirements-based evaluation is just a first step towards the full evaluation of the SensorShoe concept. Nevertheless, several important recommendations for further development of both the interface part and the general system concept can be derived:

System Concept Development

1. Communication between the PDA and the caregiver should be further investigated. The PDA may use Wifi to connect to a home-network with Internet access.
2. The PDA software needs further development, based on the structure presented in Chapter 4. This requires more information about the sensor data and communication protocols (Bluetooth and Wifi for example).
3. The specifications of electronic components of the Bracelet and SensorShoe need to be investigated. This will result in a more reliable estimation of final weight and dimensions.

Interface Development

1. A usability test should be conducted to provide more insight into the effectiveness of the GUI. The focus should be with the interpretation of real time gait feedback and the physical therapy cues.

The next paragraph will present a more detailed approach for the further development of the user interface, based on a usability test.

5.2.Usability Test

Though the GUI for the PDA has been designed according to GUI design guidelines, there's no guarantee that the interface is as effective as expected. To verify the effectiveness of the interface, a usability test can be conducted. The test may indicate flaws in the current design, as well as recommendations and feedback from actual users.

Based on the evaluation of requirements, the following aspects are relevant for further investigation in a usability test.

1. Is the interface structure obvious and effective?
2. Are graphical elements (icons, graphs) recognised as expected?
3. Do users understand and/or accept physical therapy assistance?
4. Do users understand and/or accept real time gait feedback?

To investigate the first three aspects, a functional prototype can be used. The functional prototype should at least allow the user to perform some (interactive) tasks. To investigate the fourth aspect, a functional prototype of the tactile feedback module is required.

GUI Prototype

A functional prototype of the user interface has been developed[36]. The prototype is based on HTML and Javascript, and allows the user to perform simple tasks. The following functions are supported:

- *Simulate real-time feedback* – User can start real time feedback mode, and control the rhythm speed using the PDA. Tactile feedback is simulated graphically.
- *Simulate PT feedback* – User can start physical training. Two examples have been included. The user can ask for more information about the exercise, and evaluate the exercise afterwards.
- *Show progression* – An overview of weekly and monthly progression can be shown. User can select weekly or monthly view.
- *Check system status* – The user can check the battery status and connection status of each of the three system modules

Besides the user actions, the interface prototype also simulates several external conditions:

- Start physical training alarm
- Simulate low battery
- Simulate lost signal
- Simulate incoming message from caregiver

[36] *Appendix D contains screenshots of the prototype*

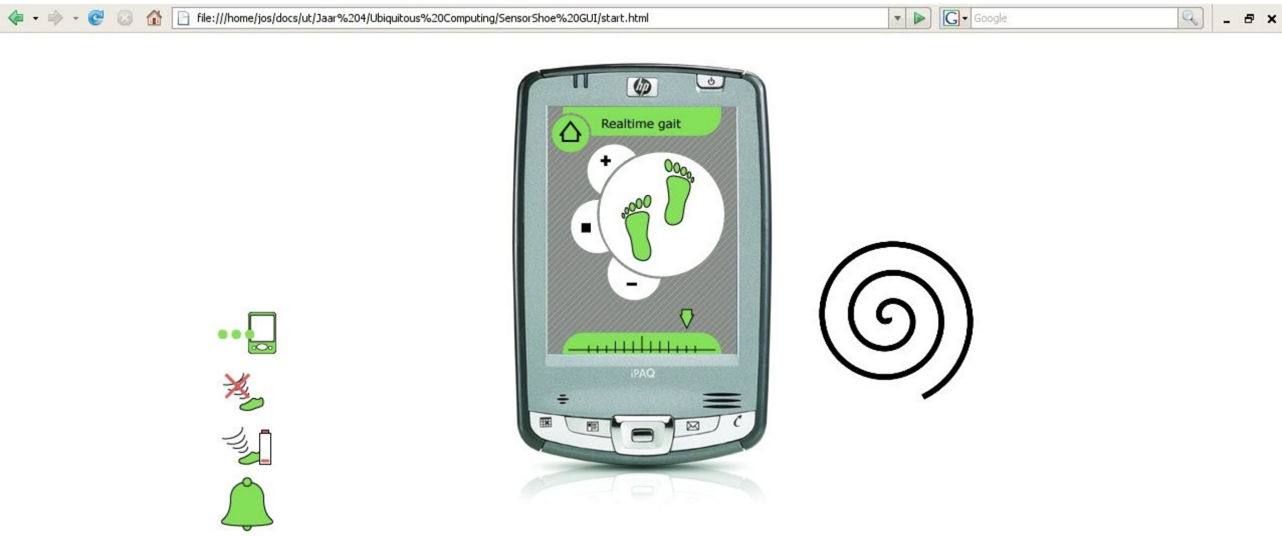


Fig. 5: Screenshot of the prototype in a webbrowser

Limitations

The prototype is only meant to be used for communication (showing how the interface would work) and usability testing purposes. Integration with other prototype parts, such as sensors or tactile feedback actuators, isn't feasible with this prototype.

Furthermore, at the moment the prototype only runs on a 'normal' computer. It hasn't been tested on actual PDA's or other mobile devices. However, it does provide a simulated on-screen PDA. This limitation should be taken in to account during the usability tests.

Test Setup

To test the usability of the PDA GUI, a group of users can be asked to perform certain tasks with the interface. An introduction to the subject of the project would be useful to give the test persons an impression of what they may expect.

Test Group

The test group should represent both general and extreme characteristics of the users, as described in Chapter 3. For a first test, a group of 15 persons would be a good trade-off between significant quantity and available time.

Environment & Participants

The usability test can be conducted in a normal environment. The only requirements are a (mobile) computer with an internet browser and the functional prototype. To receive user input it is possible to use a normal mouse, but it would be better to use a touch screen if available. This would be a better simulation of the actual PDA interface.

Besides the test person, a facilitator should be present to provide the user with tasks, and help the user if needed. The facilitator also introduces the subject and the functional prototype. Furthermore, another member of the test team should record the actions of the user. This can be done by writing notes, or by automatically logging the computer input/output actions.

Tasks

Using the functional prototype, the users can be asked to perform the following tasks.

1. Suppose you'd like to make a walk and receive assisting cues. Start the appropriate program on the PDA.
    1. [At the real time gait screen] You're receiving cues. Lower the speed of the cues.
    2. [At the real time gait screen] You've arrived at your destination. Stop the cues.
    3. [At the real time gait screen] Go to the main screen
2. You want to do your daily physical therapy exercises. Start the appropriate program on the PDA.
    1. [At the PT screen] Suppose you want more information about the current exercise. Find the appropriate support on the PDA.
    2. [At the PT screen] After finishing the exercise, express your opinion about the exercise
3. You want to check the progression of your exercises. Start the appropriate program on the PDA.
    1. [At the progression screen] Which days of the last week were most effective?
    2. [At the progression screen]Go back to the main screen

The functional prototype can also be used to simulate external actions.

1. [Facilitator starts the 'low battery' message]
    1. What's going on?
    2. What would you do now?
2. [Facilitator starts the 'out of range' message]
    3. What's going on?
    4. What would you do now?

The tasks and simulated events should be prepared by writing or printing them on cards. The cards can be used by the facilitator to instruct the test person. The results of the above tasks should provide insight in to the understanding and effectiveness of the SensorShoe interface.

5.3.Conclusions

This chapter conducted a first evaluation of the SensorShoe concept by reviewing the system requirements of Chapter 3. The results indicate further development should focus on the following aspects:

1. Communication between the PDA and the caregiver
2. The PDA software
3. The specifications of electronic components
4. The effectiveness of the GUI

The first three aspects are beyond the scope of this research, as they are mostly related to component design and detailed software design. The fourth aspect, regarding the user interface, is relevant for this research and was further investigated.

A plan for more comprehensive tests of the PDA GUI has been presented. To conduct this usability test, a functional prototype should be used. This functional prototype is already available, and allows a user to perform several interactive tasks with the PDA GUI.

Several recommendations on the test environment, set up and task examples have been presented, which should result in a useful usability test. The test should at least indicate problems with the understanding and acceptance of the interface.

6.Literature

6.1.Papers, Publications and Proceedings

1. Fernandez del Olmo, M. et al, "Evaluation of the effect of training using auditory stimulation on rhythmic movement in Parkinsonian patients—a combined motor and [F]-FDG PET study ", Department of Medicine-INEF-Galicia, Laboratory of Neuroscience and Motor Control (NEUROcom), Universidad de A Coruna, Spain , 2005
2. Gutihrrez, E. et al, "Virtual images as a perceptual orthesis to assist Parkinson's disease gait disorders ", Proceedings of The First Joint BMES/EMBS Conference Senring Humanity, Advancing Technology, Georgia, USA
3. Han, Iung-Sw et al, "Development of the Gait Assistant Mobile Robot Using Ergonomic Design ", Department of Precision Mechanical Engineering, Hanyang Universify, Seoul, South Korea , April 2004
4. Jyrinki , T, "Perception of Small Device Vibration Characteristics - Test Facilities Setup and Study ", Helsinki University of Technology, October 12, 2004
5. Jones, L. et al, "Development of a Tactile Vest", Department of Electrical Engineering, Massachusetts Institute of Technology, USA, April 2004
6. Langston, J.W., "PD: More the a Movement Disorder". New York, USA: Parkinson's Disease Foundation, 2006
7. Lee, J.C et al, "Haptic Pen: Tactile Feedback Stylus for Touch Screens", MITSUBISHI ELECTRIC RESEARCH LABORATORIES , December 2004
8. Lewis, G.N. et al, "Stride length regulation in Parkinson's disease: the use of extrinsic, visual cues", University of Auckland, New Zealand , published in "Brain", 123, 2077–2090, 2000
9. Lünenburger et al, Review "Biofeedback for robotic gait rehabilitation ", published in Journal of NeuroEngineering and Rehabilitation , January 2007
10. Luk, J. et al, "A Role for Haptics in Mobile Interaction: Initial Design Using a Handheld Tactile Display Prototype ", published in proceedings of ACM Conference on Human Factors in Computing Systems (CHI'06).
11. Martin JP. Locomotion and the basal ganglia. In: Martin JP. The basal ganglia and posture. London: Pitman Medical; 1967.
12. Melnick, M.E. et al, "Gait analysis and Parkinson's Disease", published online at "Rehabilitation management", www.rehabpub.com,August 2002. Last visited May 9th, 2007
13. Morris, M.E, "Movement Disorders in People With Parkinson Disease: A Model for Physical Therapy", published in "Physical Therapy", Volume 80, Number 6, June 2000
14. Morris, M.E et al, "The biomechanics and motor control of gait in Parkinson disease", School of Physiotherapy, La Trobe University, Australia , April 5 2001
15. Morris, S.J, "A Shoe-Integrated Sensor System for Wireless Gait Analysis and Real-Time Therapeutic Feedback ", Massachusetts Institute of Technology, 2004
16. Paradiso, J.A et al, "Interactive Therapy with Instrumented Footwear ", Responsive Environments Group, MIT Media Laboratory Cambridge, MA USA 02139 , February 2004
17. Peppe, A. et al, "Does gait analysis quantify motor rehabilitation efficacy in Parkinson's disease patients?", Fondazione Santa Lucia, Roma, Italy, November 2006
18. Stone, D. et al, "User Interface and Interaction Design", The Open University, Published by Elsevier, 2005

19. Scheibe, R. et al, "Tactile Feedback at the Finger Tips for Improved Direct Interaction in Immersive Environments , Volkswagen AG, Group Research, January 2007
20. Tsukada, K. et al, "ActiveBelt: Belt-type Wearable Tactile Display for Directional Navigation ", Graduate School of Media and Governance, Keio University, Japan, June 2004
21. van Wegen, E. et al, "The effect of rhythmic somatosensory cueing on gait in patients with Parkinson's disease ", published in "Journal of the Neurological Sciences", 248, 2006
22. van Wegen, E. et al, "The effects of visual rhythms and optic flow on stride patterns of patients with Parkinson's disease ", Department of Physical Therapy, VU University Medical Center (VUmc), Amsterdam, The Netherlands, June 2005

6.2.Internet Sources

1. "The GaitShoe project", http://www.media.mit.edu/resenv/GaitShoe/index.html, visited in May 2007
2. "Parkinson's Disease at Wikipedia", http://en.Wikipedia.org/wiki/Parkinson's_disease, visited on 22-3-2007
3. "Parkinson's Disease Foundation", http://www.pdf.org, visited on 22-3-2007
4. "Bluetooth Technology Brief", http://www.silicon-press.com/briefs/brief.bluetooth/index.html, visited on May 9th, 2007
5. "PDA Specifications Example", http://www.pdashop.nl/product/19068/hp-ipaq-hx2490.html#specificaties, visited on May 7th 2007
6. "The E-Skin Lab", http://www.e-skin.ch/, visited May 2007
7. "Kinestetic Interfaces based on Hasser" - http://www.hitl.washington.edu/scivw/scivw-ftp/publications/IDA-ps/HAPTIC2.PS
8. The Frequently-Asked Questions about Parkinson's Disease. New York, USA: Parkinson's Disease Foundation, 2006, http://www.pdf.org, visited in May 2007

Appendix A – Feedback Selection

Audio

There are three types of audio that can be used for feedback, namely rhythmic earcons, spoken text or music. The audio can be presented to the user trough a speaker, which may be implemented by the one of the following techniques.

Speaker	Pro's	Con's
A speaker can be placed on a PDA or on the SensorShoe it self.	The user can hear the clues of the SensorShoe directly.	Other people in the surrounding area of the user can hear the clues of the SensorShoe: this can be very annoying.
		This solution can be very stigmatising, since the people around the user will hear everything. The user can get too embarrassed to even want to use the SensorShoe.

Earphone	Pro's	Con's
To prevent the stigmatising effect, the feedback can be given via a earphone.	No stigmatising effect, since only the user can hear the feedback.	By wearing an earphone, the user might not hear any other sound. In traffic, this can be very dangerous.
	No irritation of surrounding people.	

Hearing aid	Pro's	Con's
This is a device which is already used for providing hearing aid. The device is place behind the ear of the user and amplifies the surrounding sounds.	No stigmatising effect, since only the user can hear the feedback.	Signals of the SensorShoe and signals from the 'outside' may interfere, increasing the workload of the user.
	No irritation of surrounding people.	
	The user can still hear surrounding sounds, since the hearing is not cut off.	

Visual

For visual feedback, two forms of output are used for gait feedback, namely “Visual rhythm cues” and “Visual patterns”. Rhythm cues use the same principle as audio cues. Visual patterns may be in the form of line patterns or 'footstep patterns'. Several technical implementations are discussed below.

Light signals	Pro’s	Con’s
The device provides light signals to the user. This can represent a rhythm to improve the users gait.	It’s a cheap and easy solution	The surrounding people can see the light signals. As described above; this can be very annoying and stigmatising

Cue Projection	Pro’s	Con’s
The cues can also be projected on the ground. The user can adjust the gait based on these cues	Visual cues should be easily understandable for the user	The surrounding people can see the light signals. As described above; this can be very annoying and stigmatising

Virtual	Pro’s	Con’s
With a head-up display it is possible to create an augmented reality. Virtual elements are added to the reality.	By adding cues to the users reality, its easy to adjust the gait.	A head-up display is extremely expensive.
	Surrounding user do not see the augmented reality elements.	The be able to provide a augmented reality, the user should wear a large system on its head. It is no possible to make small VR solutions.
		A fully working VR solution is not yet feasible.

Computer screen	Pro’s	Con’s
When using a portable computer screen (i.e. PDA) the display can be used to provide the cues.	The display is only visible for the user, so there is no stigmatising effect and it is not annoying for other users.	The user always has to look at the PDA while walking
	The costs (of development and implementation) are not as high as a virtual reality solution. This is feasible already, a VR solution is not.	
	A computer screen can provide all kinds of feedback; icons, colours, movement on the screen etc.	

Tactile

Tactile feedback uses the skin of the user to send information. The information may be a rhythm or a direction, or a combination of both. Possible technical implementations are presented in the tables below.

Rhythmic taps	Pro's	Con's
The device on the body of the user provides a rhythmic feeling. The user senses the taps and adjusts the gait.	The technique for this can be small and therefore 'invisible' for other people.	A single tap could easily be mistaken for other movements or touches.
	Easy to adjust gait	

Electronic pulses	Pro's	Con's
Via electrodes an electronic pulse can be given to provide a rhythm.	The technique for this can be small and therefore 'invisible' for other people.	Electronic pulses can be very dangerous for people with weak harts.
	The technique for this can be small and therefore 'invisible' for other people.	Depend on variable factors such as humidity and skin characteristics.

Vibration	Pro's	Con's
Just like a rhythmic tap, the vibration is a small feeling placed on the users skin.	Higher chance of being noticed (compared to rhythmic taps).	After a while the user may be annoyed by the vibrations.
	The technique for this can be small and therefore 'invisible' for other people.	

Movement on skin	Pro's	Con's
Sliding an object over the skin can be used to give a sense of direction to the user	The technique for this can be small and therefore 'invisible' for other people.	Movements on skin can't be used for setting a certain rhythm.

Pinching / Squeezing	Pro's	Con's
Mechanically pinching or squeezing the skin	The technique for this can be small and therefore 'invisible' for other people.	Pinching could hurt the user.
	Pinching may be used for both directional and rhythm cues.	After a while the skin may get irritated.

Appendix B - GUI Concept Evaluations

Heuristic Evaluation

Several guidelines, as described in User Interface Design and Evaluation (Stone et all.), will be used for this[37].

General	It is often best to follow accepted conventions if your users are familiar with these.	1.1
	Most users read from left to right and from top to bottom. You should order widgets to reflect this.	1.2
	Follow the layout, text, color, and image guidelines explained in Part 4.	1.3

Primary windows	To identify primary windows, start by looking at the main task objects in the conceptual design	2.1
	A launch pad window can be a useful way to organize primary windows	2.2

Secondary windows	Message boxes should be worded so that the user understands the message. Avoid unnecessary jargon.	3.1
	Avoid using unnecessary message boxes..	3.2
	Use modal secondary windows if the situation requires immediate attention and it is important not to enter any further data.	3.3
	Use dialog boxes if additional information is required to carry out a task.	3.4

Menus	Menu items should be named so that their name indicates their purpose.	4.1
	The menu structure should be organized around the needs of the users rather than around the underlying software. Card sort can help achieve this.	4.2

Toolbars	ToolTips can help the user to understand the meaning of icons	5.1
	Design icons that users can easily recognize and understand.	5.2
	Design icons that are visually simple.	5.3
	Design icons that are informative	5.4
	Design icons that can be easily distinguished	5.5
	Design icons that represent concrete objects	5.6
	Design icons that are easy to perceive	5.7

[37] *Stone, D. et al, 2005*

Command buttons	Commands should be worded so that they clearly indicate the action that the button carries out.	6.1
	Place command buttons along the bottom of dialog boxes or up the right-hand side	6.2
	The buttons on a dialog box should be the same size and shape. Different-width buttons are acceptable if the labels are different lengths and the buttons are in a row	6.3

Text boxes	Use a text box if it is not possible to anticipate the user input.	7.1
	Do not use a text box without a list box if the GUI requires standardized information.	7.2
	The size of the text box should indicate how much information is required.	7.3
	The text box should be scrollable if it is not possible to anticipate the quantity of user input.	7.4
	If the text box is scrollable, ensure that sufficient lines are visible to give sufficient context for the person entering the text.	7.5
	Gray-out the text box if you want to show that, in a particular context, the content of the box cannot be changed.	7.6

Principles and guidelines for website design

Because these guidelines were made for a website, only the relevant guidelines for a application on a PDA will be discussed.

The structure of the site	Take into account the natural organization of the information	8.1
	Make the structure intuitive to your users	8.2

Helping the users know where they are	Create a consistent visual appearance for the site	9.1

Site maps	Always include a link to the first screen	10.1

Writing for the web	Keep the language simple and avoid jargon	11.1
	Check your spelling and grammar	11.2

Websites for users with disabilities

Also these guidelines were made for websites. Therefore, not all of them will be relevant. Only the relevant guidelines will be discussed here.

	Individual pages of a site should have a consistent and simple layout so that users with visual impairments or blind users using screen readers can more quickly navigate through a page and find the information they are trying to locate.	12.1
	Backgrounds should be kept simple, with enough contrast so that users with low vision, color blindness, or black and white monitors can read the visual clues.	12.2
	Buttons should be large, easy targets so that users with physical and mobility disabilities can select them easily from the screen.	12.3
	Functional features-buttons, scroll bars, navigational bars-should be identified as working functions rather than images.	12.4
	Blinking or constantly changing text elements should not be used, so that users with visual impairments, learning disabilities, or recurring headaches are not challenged.	12.5

Evaluations

Each guideline will be code. Firstly, the guideline will be graded with regards to each concept design. The grades will be between 0 and 2. 0 means "Does not fit the guideline at all" and 2 means "Fits the guideline fully".

Secondly, the concepts will be judged according to the potential which they have. (if the guideline is not fully met) The grades they will receive is the difference between the first grade and the potential the concept design has in the same scale as mentioned above.

The first grades will be colour coded, in order to get a better overview. Green is 2; guideline met. Orange is 1; guideline partially met. Red is 0; guideline not met.

Since the concept designs are not made into details yet, the grading is based on just the known properties of the interface. If a concept design lacks functionality, it will not receive the grade in the first guideline grading part. However, if it has the potential to have this functionality, it will receive the grades in the second guideline grading part.

		Concept 1		Concept 2		Concept 3		Concept 4		Concept 5	
		1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
General	1.1				0		0				
	1.2						0				
	1.3						0				0
Primary windows	2.1										
	2.2										0
Secondary windows	3.1	-	2			-	0			-	2
	3.2	-	2			-	2			-	2
	3.3	-	2			-	2			-	2
	3.4	-	0	-	2	-	2	-	2	-	2
Menus	4.1						0				0
	4.2		0				0		0		0
Toolbars	5.1		1		2		2		0		0
	5.2		0		0		0				0
	5.3										
	5.4		0		0		0				0
	5.5						0				
	5.6		0		0		0				0
	5.7						0				

Command buttons	6.1		0		0		0				0
	6.2		1				1		1		1
	6.3										

Text boxes	7.1	-	2	-	2	-	2	-	2	-	2
	7.2	-	2	-	2	-	2	-	2	-	2
	7.3	-	0	-	0	-	0	-	0	-	0
	7.4	-	1	-	1	-	1	-	1	-	1
	7.5	-	0	-	0	-	0	-	0	-	0
	7.6	-	0	-	0	-	0	-	0	-	0

Total score	23	13	30	9	12	14	23	8	17	14

Explanation when guidelines are not, or partially, met:

Concept 1

3.1,3.2,3.3,3.4: no secondary windows were assigned yet.

5.1: no tooltip is used.

5.2: some of the icons are the same as a tape recorder; the target group might not have great experience with tape recorders.

5.4: since the icons are simple, they might me too simple.

5.6: the icons do not represent objects but actions.

6.1: commands are only given with buttons, no words.

6.2: command buttons are on the left.

7: text input is not made into details (this is only used in the evaluation function)

Concept 2

1.1: Accepted conventions are not used. This could also be seen as a great advantage. The users will not be bothered with complex knowledge of other interfaces. This interface is simple and intuitive. The user can start to use it, without bias.

5.1: ToolTips are not used. These can be added since the interface has space left.

5.2: some of the icons are the same as a tape recorder; the target group might not have great experience with tape recorders.

5.4: since the icons are simple, they might me too simple.

5.6: the icons do not represent objects but actions.

6.1: commands are only given with buttons, no words.

Concept 3

1.1: the menu structure does not follow accepted conventions at all. There are no known menu's like this. By changing the structure, it changes the whole menu.

1.2: the header is placed on the right, the text is rotated. Also, the menu items are at the bottom.

1.3: The header text is rotated.

3.1,3.2,3.3,3.4: no secondary windows were assigned yet.

4.1: Menu items at the bottom are not named, there isn't any space to name them either.

4.2: there is no special organization, the menu items are just placed together in order to reduce used space.

5.1: ToolTips are not used. These can be added since the interface has space left.

5.2: The triangle shaped icon is difficult to recognize. It should indicate that the menu can expand, but it seems to be part of the menu shape.

5.4: since the icons are simple, they might me too simple.

5.5: the menu icons are all on one bar. They are difficult to distinguish.

5.6: the icons do not represent objects but actions.

5.7: as mentioned at 5.2 and 5.5.

6.1: commands are only given with buttons, no words.

6.2: no dialogue boxes assigned yet.

7: text input is not made into details (this is only used in the evaluation function)

Concept 4

4.2: Menu items are placed in one box to order them. They are not ordered around the needs of the user.

5.1: no tooltip is used. Difficult to add, there is no space left.

5.2,5.3,5.4,5.5,5.6,5.7: even thou no icons are used, these guideline are not met. The guidelines mean: the user should understand the menu items. In the toolbar text is used, which is difficult for the target group. Text is therefore not simple, easy to perceive etc.

6.2: no dialogue boxes assigned yet.

Concept 5

1.3: the font size will be too small. The boxes of the calendar will be are to distinguish since there small as well.

2.2: the main screen will not exist of a launch pad, but of several calendars.

3.1,3.2,3.3,3.4: no secondary windows were assigned yet.

4.1: the menu uses icons. There is no space for naming tags.

4.2: The remaining functions are located at the bottom of the interface, no special ordering.

5.1: no tooltip is used.

5.2: some of the icons are the same as a tape recorder; the target group might not have great experience with tape recorders.

5.4: since the icons are simple, they might me too simple.

5.6: the icons do not represent objects but actions.

6.1: commands are only given with buttons, no words.

6.2: no dialog boxes assigned yet.

7: text input is not made into details (this is only used in the evaluation function)

Principles and guidelines for website design (p. 413-415)

Because these guidelines were made for a website, only the relevant guidelines for a application on a PDA will be discussed.

		Concept 1		Concept 2		Concept 3		Concept 4		Concept 5	
		1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
The structure of the site	8.1						0				
	8.2		0				0		0		0
Helping the users know where they are	9.1		0				0		0		
Site maps	10.1		0				1		1		
Writing for the web	11.1										
	11.2	-	2	-	2	-	2	-	2	-	2
Total score		6	2	10	2	4	3	7	3	9	2

Concept 1

8.1: the structure is not intuitive, since it looks a lot like standard interfaces, but is different in several elements. Is can be confusing.

9.1: the background colour are different in each function, this is not consistent.

10.1: a link to the main screen is not always included. This could be included, but the screen will get very crowded.

Concept 3

8.1: all options are placed on one bar, there is no organization.

8.2: it’s difficult for users to find the menu items.

9.1: the same menu structure is not possible for “real time gait support”.

10.1: there is no button yet, but it could be added.

Concept 4

8.2: it’s not clear that the menu button is clickable.

9.1: since the function will decide the look of a page, the menu is always folded in, there is no consistency. When the menu is extracted, there is consistency.

10.1: there is no button yet, but it could be added.

Concept 5

8.2: even thou a calendar is intuitive (it's known) many calendar on one page will be confusing. (what to do with them?)

Websites for users with disabilities (p. 417-418)

Also these guidelines were made for websites. Therefore, not all of them will be relevant. Only the relevant guidelines will be discussed here.

		Concept 1		Concept 2		Concept 3		Concept 4		Concept 5	
		1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
	12.1		0				0		0		0
	12.2										
	12.3						0				0
	12.4		0		0		0				0
	12.5						0		0		
		7	0	8	0	3	0	7	0	5	0

Concept 1

12.1: Background colour change.

12.4: the buttons could also be images.

Concept 2

12.4: the buttons could also be images.

Concept 3

12.1: Since the same menu structure is not fully possible for other functions, it's not possible to create a consistent interface.

12.3: buttons are small.

12.4: the buttons could also be images.

12.5: the menu is moving in the screen.

Concept 4

12.1 See 9.1

12.5: the menu is moving in the screen.

Concept 5

12.1: only the header and buttons will be in the same style. The content style of the page will change a lot in every screen.

12.3: the buttons of the calendar cannot be large, since the whole calendar has to fit on one screen.

12.4: the buttons could also be images.

Appendix C – Sensor Specifications

Accelerometer[38]

Parameter	Conditions	Min	Typ	Max	Unit
SENSOR INPUT	Each axis				
Measurement Range		±3	±3.6		*g*
Nonlinearity	% of full scale		±0.3		%
Package Alignment Error			±1		Degrees
Interaxis Alignment Error			±0.1		Degrees
Cross Axis Sensitivity[1]			±1		%
SENSITIVITY (RATIOMETRIC)[2]	Each axis				
Sensitivity at X_{OUT}, Y_{OUT}, Z_{OUT}	V_S = 3 V	270	300	330	mV/*g*
Sensitivity Change Due to Temperature[3]	V_S = 3 V		±0.015		%/°C
ZERO *g* BIAS LEVEL (RATIOMETRIC)	Each axis				
0 *g* Voltage at X_{OUT}, Y_{OUT}, Z_{OUT}	V_S = 3 V	1.2	1.5	1.8	V
0 *g* Offset vs. Temperature			±1		m*g*/°C
NOISE PERFORMANCE					
Noise Density X_{OUT}, Y_{OUT}			280		μ*g*/√Hz rms
Noise Density Z_{OUT}			350		μ*g*/√Hz rms
FREQUENCY RESPONSE[4]					
Bandwidth X_{OUT}, Y_{OUT}[5]	No external filter		1600		Hz
Bandwidth Z_{OUT}[5]	No external filter		550		Hz
R_{FILT} Tolerance			32 ± 15%		kΩ
Sensor Resonant Frequency			5.5		kHz
SELF TEST[6]					
Logic Input Low			+0.6		V
Logic Input High			+2.4		V
ST Actuation Current			+60		μA
Output Change at X_{OUT}	Self test 0 to 1		−150		mV
Output Change at Y_{OUT}	Self test 0 to 1		+150		mV
Output Change at Z_{OUT}	Self test 0 to 1		−60		mV
OUTPUT AMPLIFIER					
Output Swing Low	No load		0.1		V
Output Swing High	No load		2.8		V
POWER SUPPLY					
Operating Voltage Range		1.8		3.6	V
Supply Current	V_S = 3 V		320		μA
Turn-On Time[7]	No external filter		1		ms
TEMPERATURE					
Operating Temperature Range		−25		+70	°C

[1] Defined as coupling between any two axes.
[2] Sensitivity is essentially ratiometric to V_S.
[3] Defined as the output change from ambient-to-maximum temperature or ambient-to-minimum temperature.
[4] Actual frequency response controlled by user-supplied external filter capacitors (C_X, C_Y, C_Z).
[5] Bandwidth with external capacitors = 1/(2 × π × 32 kΩ × C). For C_X, C_Y = 0.003 μF, bandwidth = 1.6 kHz. For C_Z = 0.01 μF, bandwidth = 500 Hz. For C_X, C_Y, C_Z = 10 μF,

Fig. 6: Datasheet for the 3D accelerometer

[38] *See http://www.analog.com/UploadedFiles/Data_Sheets/ADXL330.pdf*

Gyroscopic Sensors[39]

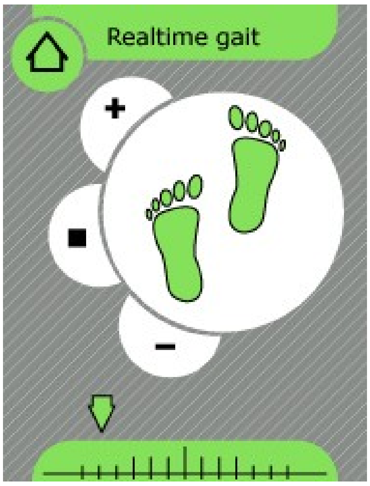
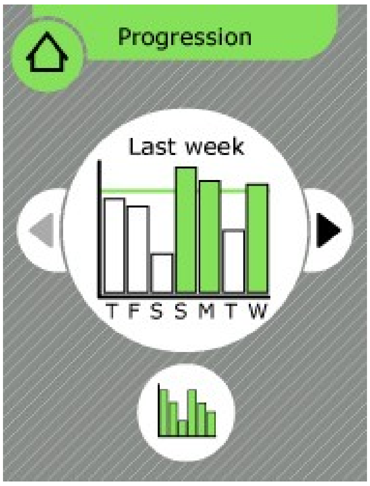
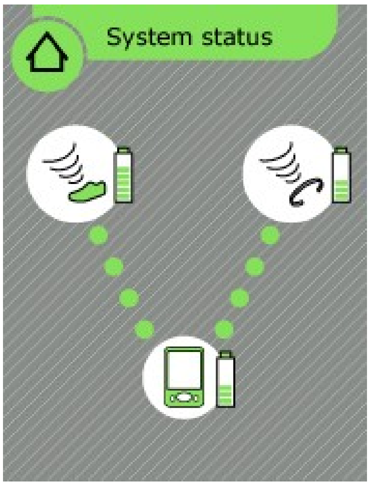
Parameters	Conditions	Min	Typical	Max	Unit
SENSITIVITY					
Full-Scale Range			±500		°/s
Sensitivity			2.0		mV/°/s
Initial Calibration Tolerance		-5		+5	%
Over Specified Temperature			±10		%
Nonlinearity	Best Fit Straight Line		<1		% of FS
Cross-axis Sensitivity			±2		%
ZERO-RATE OUTPUT					
Static Output (Bias)			1.5		V
Initial Calibration Tolerance		-300		+300	mV
Over Specified Temperature		-300		+300	mV
FREQUENCY RESPONSE					
High Frequency Cutoff	Internal LPF -90°		140		Hz
LPF Phase Delay	10Hz		-4.5		°
MECHANICAL FREQUENCIES					
Resonant Frequency	X-Axis Gyroscope	10	12	14	kHz
Resonant Frequency	Y-Axis Gyroscope	13	15	17	kHz
Frequency Separation	X and Y Gyroscopes		3		kHz
NOISE PERFORMANCE					
Rate Noise Density			0.014		°/s/√Hz
OUTPUT DRIVE CAPABILITY					
Output Voltage Swing	Load = 100kΩ to $V_{dd}/2$	0.05		Vdd-0.05	V
Capacitive Load Drive			100		pF
Output Impedance			100		Ω
REFERENCE					
Voltage Value			1.23		V
Load Drive			1		mA
Capacitive Load Drive	Load directly connected to VREF		100		pF
Power Supply Rejection	VDD= 3.0V to 3.3V		1		mV/V
Over Specified Temperature			±5		mV
POWER TIMING					
Zero-rate Output	Settling to ±3°/sec		200		ms
POWER SUPPLY					
Operating Voltage Range		3.0		3.3	V
Quiescent Supply Current				9.5	mA
Over Specified Temperature			±2		mA
TEMPERATURE RANGE					
Specified Temperature Range			0 to +70		°C
Extended Temperature Range	Performance parameters are not applicable beyond Specified Temperature Range		-20 to +85		°C

Fig. 7: Datasheet for 2D gyroscope

[39] See http://www.invensense.com/shared/pdf/IDG300_Datasheet.pdf

Appendix D – Interface Prototype

Screenshots of the PDA GUI prototype.

		
The main screen	Real Time Gait feedback	Progression of a particular physical exercise
		
Progression over the last week	System status check	Low Battery warning